PB83-151761

Index to Evaluate Lake Restoration

(U.S.) Corvallis Environmental Research Lab., OR

1980

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3.
EPA-600/J-80-402	Journal Article	PB83-151761

4. TITLE AND SUBTITLE	5. REPORT DATE
Index to Evaluate Lake Restoration	1980
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Donald B. Porcella, Spencer A. Peterson, David P. Larsen	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Environmental Research Laboratory U.S. Environmental Protection Agency Corvallis, Oregon 97333	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
same	Journal article
	14. SPONSORING AGENCY CODE
	EPA/600/02

15. SUPPLEMENTARY NOTES
Published in Journal of the Environmental Engineering Division, ASCE
Vol. 106, No. EE6, Proc. Paper 15893, December 1980, pp 1151-1169

16. ABSTRACT

A lake evaluation index (LEI) is proposed to express the overall quality of lake water based on a mathematical combination of the commonly measured limnological variables total phosphorus (TP), total nitrogen (TN), chlorophyll (CA), Secchi depth (SD), dissolved oxygen (DO), and macrophyte coverage (PMAC). Values used in the LEI are averages for the July-August period. Epilimnetic zone concentrations of TP, TN, and CA are calculated. Macrophyte coverage is expressed as the percent of the area which could potentially be occupied actually. A term net DO is calculated by summing the absolute differences between observed and saturated DO for volume increments from surface to bottom, divided by the lake volume. The LEI was developed to express the overall change in water quality that might occur when lakes are restored and to evaluate the effectiveness of various treatment methods for a wide variety of lakes.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to public	Unclassified	20
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA-600/J-80-402
JOURNAL ARTICLE

ERRATA:-- PLEASE CORRECT THE FOLLOWING
• LEI= 0.2(XCA + XMAC + XED + XDO + XTP) . . . (12)

• THE LEI VALUES OF TABLE 7 (COLUMN B) SHOULD READ.

LEI (B)
51.7
39.8

JOURNAL OF THE ENVIRONMENTAL ENGINEERING DIVISION

Journal of the Environmental Engineering Division, ASCE, Vol. 106, No. EE6, Proc. Paper 15893, pp. 1151-1169, December 1980

INDEX TO EVALUATE LAKE RESTORATION

By Donald B. Porcella,[1] Spencer A. Peterson,[2] and David P. Larsen[3]

INTRODUCTION

An ongoing program to demonstrate methods for restoring polluted lakes and preventing pollution of clean lakes is being funded with Environmental Protection Agency (EPA)/local matching (50/50) money as directed by sections 314/104(h) (Clean Lakes) of PL92-500 (Federal Water Pollution Control Act Amendments of 1972). To help evaluate the efficacy of the various restoration techniques, a subset of all the lakes being restored under this program was selected for comprehensive limnological evaluation (23).

The objectives of the detailed limnological evaluations of lake restoration projects are: (1) To determine the effectiveness of the specific restoration manipulation(s) at a given lake; and (2) to compare the effectiveness of various restoration processes on different lakes.

Two comparative approaches are used: (1) Target variables (indicators of lake state) based on the concept of nutrient balance similar to Vollenweider's analysis that began in the late 1960s (4,31,32); and (2) target variables selected to represent general lake water quality analyzed independently as well as combined in a manner to provide a single index number (Lake Evaluation Index, LEI). The individual target variables of the LEI are transformed to produce a scale of 0 (minimally impacted)–100 (maximally impacted) to facilitate comparisons.

This paper describes the basic concepts of lake quality evaluation as they relate to the development of a Lake Evaluation Index (LEI). Proposed methods are presented; undoubtedly, modifications and refinements will occur as

Note.--Discussion open until May 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. This paper is part of the copyrighted Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 106, No. EE6, December, 1980. Manuscript was submitted for review for possible publication on January 16, 1980.

[1]Principal Scientist, Tetra Tech Inc., Lafayette, Calif.
[2]Research Aquatic Biologist, Corvallis Environmental Research Lab., United States Environmental Protection Agency, Corvallis, Oreg.
[3]Research Aquatic Biologist, Corvallis Environmental Research Lab., United States Environmental Protection Agency, Corvallis, Oreg.

TABLE 1.—Classification of Lakes using Variables

Reference (1)	Dependent variable (2)	Number of variables (3)	TP (4)	OP (5)	TIN (6)	TON (7)	TN (8)	POC (9)	PP (10)	CA (11)
Brinkhurst, et al., 1960	trophic state	1								
Brook, 1965	trophic state	1								
Carlson, 1977	TSI	3	X							X
Dillon and Rigler, 1975	trophic state	3	X							X
Dobson, et al., 1974	trophic state	4	X					X		X
Harkins, 1974	standards SM	4	X							
Hayes, 1957; Hayes, et al., 1964	fish PI	3								
Hutchinson, 1938	trophic state	1								
Jarnefelt, 1958	trophic state	1								
Lueschow, et al., 1970	RTSI	5	X	X	X	X				
McColl, 1972	RTSI	9	X	X	X					X
Megard, et al., 1978	trophic state	1								
Michalski and Conroy, 1972	trophic state	6								X
Miller, et al., 1974	trophic state	1								
Mortimer, 1941	trophic state	1								
Neel, 1977	TSI	2								
Rawson, 1960	RTSI	8								X
Reynoldson, 1958	trophic state	1								
Rodhe, 1958, 1969	trophic state	1							X	

that Reflect their Limnological Conditions (24)

DO (12)	pH (13)	SD (14)	Morphology (15)	Macrophyte and algal variables (16)	Other water quality variables (17)	Ratios (18)	Other Variables: Floral (19)	Other Variables: Faunal (20)
								X
							X	
		X						
		X						
		X						
X	X				BOD_5, alkalinity			
			mean depth, in centimeters					
X								
								X
X		X		algae				
X		X			alkalinity Fe, Mn light transmission			
X		X	mean depth, (Ryder)			Fe/P		
				bioassay				
X								
			residence time			Mg/Ca		
		X	mean depth		temperature, TDS		plankton	benthos, fish
								X

TABLE 1.—

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Ryder, 1965	fish production	2								
Sawyer, 1947	trophic state	2		X	X					
Shannon and Brezonik, 1972	TSI	7	X			X			X	X
Skulberg, 1966	trophic state	1								
Stockner, 1972	trophic state	1								
Toerien, et al., 1975	trophic state	1								
USEPA, 1974	RTSI	6	X	X	X					X
Uttormark and Wall, 1975	LCI	4								
Vollenweider, 1968	trophic state	2	X				X			
Winner, 1972	RTSI	9							X	X
	frequency of use		8	4	4	2	1	1	3	8

Note: TP = total phosphorus; OP = orthophosphate P; TIN = total inorganic nitrogen; productivity; CA = chlorophyll a; DO = dissolved oxygen; SD = Secchi depth; Morphology

experience increases. Data necessary to apply the concepts of the nutrient mass balance approach are described elsewhere (24).

Lake Evaluation Index

Literature reviewers concluded that there is no universal and completely satisfactory index of lake water quality. Generally, indices are designed for specific uses and for a set of regional or local lakes. Indices are useful for decision making, prioritization, and public awareness. Ideally, a simple index of lake quality should be developed that: (1) Is not lake specific, i.e., it can be generalized to all lakes; (2) is related to all uses; and (3) is objective, independent of other variables, and easily measured. The difficulties in achieving these criteria are apparent in the variety of lake classification schemes shown in Table 1.

The LEI proposed in this paper incorporates a minimal set of limnological

Continued

(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
			X		TDS			
		X			conduc-tivity	cation		
				bioassay				
							sediment dia-toms	
				bioassay				
X		X						
X		X		X	fish kills			
		X		seston	assimila-tion	P/B, pig-ment	diversity	diversity
9	2	11	6	5	12	5	4	6

TON = total organic N; TN = total N; POC = particulate organic carbon; PP = primary = various morphological parameters.

variables to evaluate the limnological effects of lake restoration projects. The LEI is intended for a specific use although a more general applicability may eventually result. The concept is simpler than the nutrient mass balance approach, although data requirements are quite similar. The measurements relate to previous studies and in some cases conform to perception of lake problems and, therefore, to phenomena visible to the general public.

Lake quality variables can be grouped generally into hydrological, morphological, physical-chemical, and biological types. In most cases, hydrology would not be significantly affected by lake restoration activities. Changes in mixing patterns and residence times will occur in dilution/flushing projects; mixing can result from some dredging, aeration, and other projects. Some morphological variables will be greatly affected; depth and volume will be changed by dredging or outlet structure changes and diversions, or both. However, most changes will be seen in the physical-chemical interactions (nutrients, other salts, light,

and temperature) and biological responses to these changes (flora, fauna, and dissolved oxygen). Measurement of all factors related to these changes is impractical. Thus it is necessary to select target variables that indicate general water quality. The basis for the LEI concept presented in this paper is that lake water quality problems are caused largely by, or associated with, increased nutrient concentrations (eutrophication) in the lake.

For instance, an increase in lake phosphorus concentration would stimulate primary productivity producing increases in chlorophyll-a. Simultaneously, Secchi depth (higher turbidity) and hypolimnetic DO (increased biochemical oxygen demand (BOD) from decomposition of settled algae) would decrease. In this scenario, data on total phosphorus (TP), chlorophyll-a (CA), Secchi depth (SD), and DO would exemplify changes in lake water quality. It is necessary to measure nitrogen compounds (total nitrogen, TN) as well as phosphorus because nitrogen is the next most frequently limiting nutrient in lakes. Macrophytes (MAC) are an important part of lake primary production not measured by chlorophyll-a methods or most primary productivity methods, yet they have significant effects on nutrients, DO, SD, and other water quality variables and lake uses. Therefore, data on macrophytes are required.

The evaluation phase of the lake restoration program has been designed principally to analyze productivity problems. However, lake water quality problems resulting from BOD inputs would be reflected in the DO variable, and problems caused by suspended solids loadings would be reflected by the SD variable. Additional analyses would be required to determine lake restoration effects on bacteriological and other problems such as toxicity, oil spills, or salinity. Many other possible target variables (Table 1) were reviewed for possible inclusion in the LEI and were rejected because of the lack of a data base, high cost of obtaining the data, lack of information related to their significance or application, or lack of a suitable concept for relating to use.

Definition of Target Variables of LEI

The target variables considered in the previous section for developing an LEI are: (1) Secchi depth (SD); (2) total phosphorus (TP); (3) total nitrogen (TN); (4) chlorophyll-a (CA); (5) dissolved oxygen (DO); and (6) macrophytes (MAC). These variables have the following attributes: (1) They span most of the major water quality problems that affect uses of lakes; (2) they duplicate most of the parameters contained in other indices and in nutrient mass balances; and (3) they are commonly, and for the most part, easily measured. The attribute of the group of variables is that the range of lake types that can be evaluated is broader than if a single or fewer variables were included.

Sampling

The July–August period is specified for all variables used in the LEI. Generally, time of day is critical, and lake measurements should be restricted to 1000–1400 standard time, preferably closer to 1200. Variables such as CA, open water primary productivity, and nutrients, relate principally to measurements made in the water column in the photic zone (defined as the layer enclosed between the water surface and the shallow of the lake bottom or water depth at light

intensity equal to 1% of the incident surface intensity). The photic zone is defined as two times SD. The depth of light penetration into lakes is controlled by the sun and climate, season, water color, and turbidity. Light controls photosynthesis (thus primary production) in lakes, and therefore defines zones that limit the depth of phytoplankton net production and, in large part, the distribution of macrophytes. Although the mixed zone (epilimnion) and the photic zone can be different ecologically, reasonable assumptions are that photic zone and epilimnion concentrations are similar or that target variables vary principally with the epilimnion. Thus, except for the macrophyte zone, the epilimnion is used in calculations of target variables and all measurements must be taken in this layer. The selection of epilimnion samples is supported because correlation of TP and CA using surface samples or photic zone samples indicated that differences in equation coefficients were minimal (2,4).

Transformation of Variables

In the following paragraphs each target variable is briefly analyzed, defined, and transformed. This transformation to a scalar range facilitates combination and comparisons between variables for different restoration projects. The approach suggested here derives from Carlson's (2) method of transforming SD data.

Carlson's (2) approach was to take the greatest and least expected values for SD and assign a rating scale of 0–100; 100 was assigned to essentially no light transmission; 0 was assigned to the maximum expected light transmission and the Beer-Lambert Law was assumed to apply. For the other variables, the transformation of measured values to rating values are not as clearly defined even though a reasonable range of minimum impact (0) to maximum impact (100) can be assigned. The other variables are not as simply related to a single target as SD is for clarity (light penetration). Carlson (2) handled this by relating TP and CA to SD.

Secchi Depth.—The SD is a common and simple method for estimating the depth of light penetration in lake waters. During the sampling period, SD will vary mainly according to the concentration of phytoplankton. Inorganic turbidity and highly colored waters can affect SD, and it may become necessary to separate lakes into classes or types.

To relate lake trophic state to a measurable variable, Carlson (2) assumed that light intensity (I) as measured by Secchi disk disappearance decreases with depth (Z) according to the Beer-Lambert Law:

$$\ln I/I_0 = -nZ \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Increased turbidity owing to phytoplankton and other suspended material would increase the value of the extinction coefficient (n) and cause the disk to disappear at shallower depths.

Using a maximum limit for SD of 64 m [41.6 m was the maximum reported in Hutchinson (11), and 43.25 m was reported for Lake Tahoe (9)]. Carlson (2) developed a trophic state index (TSI) for SD:

$$\text{TSI} = 10\,[\log_2(64) - \log_2(\text{SD})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\text{TSI} = 10\,[6 - \log_2(\text{SD})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Carlson's TSI was equated with the scalar rating value, XSD, for use in the LEI as follows:

$$XSD = 60 - 14.427 \ln (SD),\ XSD \leq 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

(All rating values are confined to the range 0–100 to prevent undue weighting of single variables on the LEI.) Comparison of SD and the rating values are shown in Table 2.

Total Phosphorus.—The shape of the curve relating the scalar value (XTP) to TP July–August average epilimnetic concentration is based on relationships between chlorophyll-a and TP (2,4,12), and chlorophyll-a and SD (2,6). These relationships suggest that the quality of lake water is logarithmically related to TP; higher TP results in greater algal populations and lesser results in transparency, but the impact of the rate of concentration increase is less at higher concentrations.

TABLE 2.—Rating Scale for Lake Water Quality Variables

Rating (X) (1)	Secchi depth, in meters (2)	Total P, in milligrams per cubic meter (3)	Total N, in milligrams per cubic meter (4)	Chlorophyll-a, in milligrams per cubic meter (5)	Net DO, in milligrams per liter (6)	Macrophytes, percent of available lake area covered (7)
0 (minimally impacted)	64.0	0.75	5.2	0.04	0.0	0
10	32.0	1.5	10.4	0.12	1.0	10
20	16.0	3.0	20.8	0.34	2.0	20
30	8.0	6.0	41.6	0.94	3.0	30
40	4.0	12.0	83.2	2.61	4.0	40
50	2.0	24.0	167.0	7.23	5.0	50
60	1.0	48.0	333.0	20.0	6.0	60
70	0.5	96.0	666.0	55.5	7.0	70
80	0.25	192.0	1,330.0	154.0	8.0	80
90	0.125	384.0	2,670.0	426.0	9.0	90
100 (maximally impacted)	≤0.0625	≥768.0	≥5,330.0	≥1,180.0	≥10.0	100

The limits of Carlson's (2) scalar values include the lower TP measurements, but the higher values ($\geq 768\ mg \cdot m^{-3}$) must be defined as equal to 100. Oligotrophic lakes have lower values on the order of $1\ mg \cdot m^{-3}$ [Waldo Lake, Oreg. (18); Lake Tahoe, Calif.-Nev., $0.9\ mg \cdot m^{-3}$ (9)]. Eutrophic lakes exhibit a wide range of maximum values of springtime orthophosphate P or summer TP [$150\ mg \cdot m^{-3}$ (12); $330\ mg \cdot m^{-3}$ (20); up to $3{,}660\ mg \cdot m^{-3}$ of median TP (29)].

Carlson's (2) equation transformed for use in the LEI is:

$$XTP = 4.15 + 14.427 \ln TP,\quad XTP \leq 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Total Nitrogen.—Although Sawyer (27) related total inorganic nitrogen to incipient eutrophication problems, Leuschow et al. (17) proposed that total organic N also be used as a variable for lake characterization. Because total N would include inorganic nitrogen forms (potential growth of primary producers), as

well as particulate nitrogen (primary producers), it was chosen as the LEI target variable. Unfortunately, total N also includes detrital N and soluble organic forms of N that might or might not be available for growth; in addition, there is greater likelihood of analytical error in the Kjeldahl measurement and this, plus its difficulty and cost, often leads to its exclusion as a measured parameter. These disadvantages and the observation that frequently nitrogen in not limiting or is added by nitrogen fixing blue-green algae suggest that TN should not be used in the evaluation. However, its importance as a toxicant to humans (nitrate) and fish (free ammonia), oxygen consumption, and algal growth, require that it be measured and considered.

The transformation of TN to the rating scale (XTN) was determined in relation to TP. The N/P ratios for phytoplankton average about 16/1 (mole/mole) or 7/1 (weight/weight). Thus TN is equivalent to 7.0 TP and the scalar rating is:

$$XTN = 14.427 \ln TN - 23.8, \quad XTN \leq 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Equivalent values of XTN and TN are shown in Table 2.

Oligotrophic lakes show values of TIN (TN data incomplete) to be about 1–50 $mg \cdot m^{-3}$ [Waldo Lake, Oreg., 50 mg $N \cdot m^{-3}$ (18); Lake Tahoe, Calif.-Nev., 0.9 mg $N \cdot m^{-3}$ (NH_4^+ assumed to be 0.0) (9)]. Values for eutrophic lakes vary widely [710 mg $TIN \cdot m^{-3}$ (20); median value 7,355 mg $TIN \cdot m^{-3}$ (29)], and XTN must be restricted to 100 when including values greater than 5,330 $mg \cdot m^{-3}$.

Chlorophyll-a.—Many investigators have correlated CA and phosphorus loading and thereby related a level of eutrophication to chlorophyll levels. These approaches have a logarithmic functional relationship in common; thus, loss of beneficial use occurs with increasing CA concentrations, but detriment increases more rapidly at low concentrations and less rapidly at higher concentrations. Because CA concentrations are a function of other variables and, like SD, can be related to a perception of a lake system's quality, epilimnetic CA concentrations can be used to define quality levels for the other target variables.

Dobson et al. (5) defined chlorophyll-a as a function of clarity using the inverse of SD in meters, i.e., CA = 1.14 (30/SD). Carlson (2) used a similar, nonlinear approach:

$$\ln SD = 2.04 - 0.68 \ln (CA) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Solving for CA and transforming to the scalar (XCA) related to SD as was done for TP provided the following equation:

$$XCA = 30.6 + 9.81 \ln (CA), \quad XCA \leq 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Equivalent values of XCA and CA are listed in Table 2. Concentrations of chlorophyll-a in oligotrophic and eutrophic lakes (Table 3) are encompassed by the equation. These relationships are used even though, contrary to Carlson's assumption, CA and SD correlate only under some circumstances and frequently they measure different factors.

Dissolved Oxygen.—There are several approaches for analyzing DO data (15); hypolimnetic DO has been used to characterize lake trophic status; DO deficit and deficit rates have been suggested; hypolimnetic concentrations, a transformed minimum DO, and DO concentration have also been used.

These approaches all have disadvantages. The hypolimnion represents a water

layer which has a continuous DO demand due to heterotrophic breakdown of organic matter (excess production) but little or no replenishment from other sources (atmosphere, diffusion processes, inflow, or primary productivity). Almost all of the demand for hypolimnetic DO comes from organic material settling through the hypolimnion or contained in the sediments. Consequently, oxygen demand by the sediments represents previous history of the lake system and changes in lake nutrient and productivity status may not be reflected in a change in DO demand without a significant time lag. Significant changes in nutrient inflow that are applied over a long period of time, or changes in existing sediment chemical composition, or both, would be required before hypolimnetic DO patterns would be significantly affected.

Ideally, hypolimnetic DO would be the most useful indicator of respiration, and respiration would be relatively independent of time and space effects on

TABLE 3.—Maximum and Minimum Chlorophyll-a Values Measured in Lakes

Reference (1)	System or lake (2)	Chlorophyll-a,[a] in milligrams per cubic meter	
		Maximum values (3)	Minimum values (4)
5	Great Lakes	25.4	0.4
12	16 Iowa lakes	262.2	6.8
12	16 Iowa lakes and compiled data[b]	400.0	0.3
29	209 lakes in National Eutrophication Survey	381.0	1.0
33	five Colorado lakes	34.1	1.0
28	55 Florida lakes (mean)	39.1	1.8
7	ELA lakes	327	<1.0[b]
18	Waldo Lake, Oregon	1.64	0.13 (mean, 0-60 meters deep)
10	Lake Tahoe, California-Nevada	<1.0	0.1
Extremes		400	0.1

[a] Not all data corrected for pheophytin-a.
[b] Estimated from graphical data.

sampling. Unfortunately, the volume of the hypolimnion of many lakes is small, relative to the lake bottom area, or is nonexistent. Thus, many approaches described in the literature cannot be used because of morphological differences in lakes.

As a first step in developing a target variable based on DO, we have assumed that it is possible to calculate the instantaneous total lake equilibrium DO (EDO, kg/lake) from atmospheric pressure and the temperature-depth profiles. This value (EDO) is defined as the reference value for a clean-water lake. Comparison of this value with the measured instantaneous total lake DO (CDO, kg/lake) allows analysis of the relative quality of the lake ecosystem with respect to physical processes and respiration/photosynthesis.

However, in highly productive lakes that stratify during the summer, DO

supersaturation can occur in the surface waters while zero DO or undersaturation occurs in the bottom waters. Addition of these quantities (a positive and a negative) to obtain total DO could result in essentially no difference in comparison with EDO. Both supersaturation and undersaturation could be considered indicative of degraded conditions in a lake. Thus, the incremented absolute values of the net difference with depth between EDO and CDO will be used:

$$\text{net DO} = \frac{\sum_{i=0}^{i=Z\max} |(\text{EDO} - \text{CDO})_i| \, \Delta V_i}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

in which Zmax = maximum depth; ΔV = the volume at a selected and convenient depth increment; and i = the increment.

Net DO is described from DO and temperature profiles for the July–August period. Significant (≥5%) inflow/outflow or volume changes would require adjustment of EDO estimates. Without contrary information, the scalar value (XDO) is assumed to be a linear function of the net DO. The best situation (XDO = 0) would occur if net DO were zero, and a very poor quality (XDO ≥ 100) would exist if net DO is ≥ 10:

$$\text{XDO} = 10\,(\text{net DO}), \quad \text{XDO} \leq 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Equivalent values of XDO and average net DO are listed in Table 2.

Macrophytes.—So far, variables that relate principally to the pelagic area of lakes, i.e., the deeper zone of open waters, have been defined. However, eutrophic lakes are often relatively shallow and even deep lakes have shallow regions (the littoral zone) typical of neither the pelagic zone nor the drainage basin which nourishes the lake. The littoral zone contains macrophytes which mark the transition from rooted-upland or terrestrial-producer organisms to planktonic producers of the open water ecosystem. Macrophytes (macroscopic algai, mosses, and vascular plants or weeds) may be attached, emergent, submerged, submerged with floating leaves, or free-floating forms.

Our concern is to develop a relationship between macrophyte biomass and nutrient variables (water concentrations, sediment concentrations, loadings) within the littoral zone because macrophyte problems occur in approximately one-third of the funded Clean Lakes demonstration projects. Generally, high quality lakes have few macrophytes and lower quality lakes have more macrophytes in the littoral zone.

The area of the lake subject to growth of macrophytes can be defined as the area encompassed by the lake margin and whichever is shallower: either the 10 m line hydrostatic limit or the photic zone, the depth at which light becomes limiting to vascular plant distribution and growth (2 × SD). The percent of this area that is actually covered by vascular plants is defined as the target variable. Only relatively crude surveys during the growing season (July–August) are needed to assess the percent of that area actually covered by the vascular plants. The target variable, i.e., percent macrophyte area covered (PMAC), could be assessed in terms of a rating value (XMAC) as a simple percentage:

$$\text{XMAC} = \text{PMAC} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The system impacted least would be defined as having 0% cover and the one

impacted most as having 100% cover. Thus the equivalent values of XMAC and PMAC are identical (Table 2).

Proposed Formulation of I.EI

Rating Values and Trophic Levels.—The target variables used for evaluation are neither mutually exclusive nor independent variables. Their comparison as a rating value for a given lake will not necessarily agree. Furthermore, each

TABLE 4.—Estimates of Eutrophication Levels Associated with Specific Variables that Measure Lake Quality

Variables (1)	Oligotrophic (2)	Eutrophic (3)	Reference (4)
Variables in I.EI			
chlorophyll-a photic zone mean, in milligrams per cubic meter	<4	>10	22
	0.3–2.5	5–140	26
	<4.3	>8.8	5
	<1	>6	2
overall average	<2.75	>8.7	3
peak photic zone, in milligrams per cubic meter	<3	>20	13
Secchi depth, in meters	>6	<3	5
total inorganic nitrogen, in milligrams per cubic meter		>300	27
total inorganic phosphorus, in milligrams per cubic meter		>10	27
Non-I.EI variables			
Primary Productivity $^{14}CO_2$ uptake			
mean daily, in milligrams of carbon per square meter per day	30–100	300–3000	25
total annual, in grams of carbon per square meter per day	7–25	75–700	25
mean daily, in milligrams per square meter per day	<200	>750	13
Hypolimnetic DO deficit rate milligrams of oxygen per square meter per day	<250	>550	21
Nutrient Loading (at mean depth, $\bar{z}$)			
TP, in grams per square meter per year		>0.3 (20 m) >0.8 (100 m)	31
TN, in grams per square meter per year		>4 (20 m) >1 (100 m)	
Algae, in number per liters	<2,000	>15,000	13
Biomass, in milligrams per liter	<5	>10	
Cell volume, in cubic millimeters per liter	<5	>30	
Rotifers, in number per liters	<10	>250	
Microcrustacea, in number per liters	<1	>25	
Species diversity	low (high is mesotrophic)	low	

represents slightly different lake characteristics. Thus, the rating values are not expected to agree among themselves for a lake or set of lakes. This is apparent when comparing rating values for complementary variables such as macrophytes and chlorophyll-a.

Morphological (depth) and hydrologic (flow-through rate) factors significantly affect the nutrient, DO, macrophyte, and chlorophyll-a concentrations in lakes. For these reasons, it is important to look at the individual target variables in comparing the effects of specific lake restoration projects.

Various suggested levels of chlorophyll-a concentrations have been related to trophic levels and these were averaged (3) to obtain reasonably quantitative definitions of trophic state (Table 4). Similar values have been estimated for SD, inorganic nitrogen (TIN) and orthophosphate (TIP) as well as other parameters (Table 4).

TABLE 5.—Concentrations Associated with Trophic State Defined by a Relative Ranking Obtained from NES Data on 209 Lakes (30)

Parameter (1)	Oligotrophic (percentile >83.3) (2)	Eutrophic (percentile <70) (3)
median total P, in milligrams per cubic meter	<14	>25
median dissolved P, in milligrams per cubic meter	<8	>11
median total N, in milligrams per cubic meter	<140	>180
median chlorophyll-a, in milligrams per cubic meter	<4.8	>7.4
minimum observed DO, in milligrams per liter	>7.2	<6.2
mean Secchi depth, in meters	>2.8	<2.0

Note: Estimation based on three sampling times (spring, summer, and fall) and one or more sampling sites and more than one sampling depth.

Good agreement with the values in Table 4 was obtained when 209 NES lakes were ranked and the summed percentile rankings for six separate parameters were used to provide a breakpoint of ≤500 for oligotrophic lakes and ≥420 for mesotrophic lakes (29). These totals correspond to average percentile limits of ≤83.3 and ≥70.0 for oligotrophy and eutrophy, respectively. Values of parameters corresponding to these percentiles (Table 5) indicated very narrow ranges "defining oligotrophic and eutrophic" over the rather broad spread of actual concentrations shown in Table 3 for the rating value. The values in Table 2 were plotted and the levels associated with different trophic states (Table 5) were noted for comparison (Fig. 1). The variables that define different trophic states agree surprisingly well and in defining relative limits, show that rating values of less than 45 indicate oligotrophy and values greater than 50 indicate eutrophy.

The range of scalar values reflecting our perception of lake quality is quite narrow. Two factors could account for this: (1) There may be only two roughly

definable states of lake quality as far as beneficial uses are concerned, i.e., noneutrophic and eutrophic; and (2) the actual range of causative factors that define lake quality status is very narrow (factor of two) in comparison to the three-four orders of magnitude range in actual measurements of the target variables.

LEI.—Although each target variable will be used by itself to evaluate lake response, a grouping into a single numerical index was devised to compare the responses of various lakes of the lake restoration program. The formulation of the LEI was based on a number of assumptions, limited data, and as yet untested concepts of the writers. The formulation of the LEI is hypothetical and, to a certain extent, arbitrary. It is proposed as a hypothesis that will be tested by applying synoptic data obtained from the evaluation of lakes funded for restoration under the Clean Lakes Program or from literature or NES data (30). The LEI is not intended to be unalterably structured. Tests of the concept may result in some alteration of the LEI formulation.

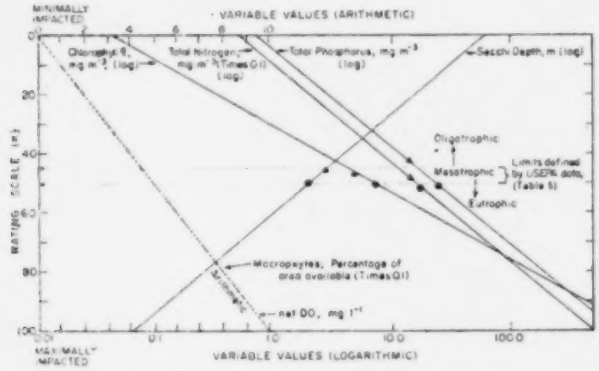

FIG. 1.—Relation between Rating Values and Variable Values Compared to Eutrophication Levels

The LEI has a range of 0–100 and was obtained by averaging specific target variables. Because primary productivity in lakes is the sum of phytoplankton productivity and littoral zone productivity, the rating values of these two variables (XCA, XMAC) were included; XSD and XDO were included directly; the nutrient variable was assumed to be XTP because of its typical importance but XTN could be (and will be for testing the hypothesis) substituted. Also, nitrogen fixation could compensate for TN and force TP to be the limiting factor. Generally, if phosphorus is limiting, lower rating values for TP will be obtained than for TN. This comparison (XTP versus XTN) is one way of determining whether to use XTP or XTN, i.e., the lower rating value of either XTP or XTN could be used. These considerations resulted in the following equation:

$$LEI = 0.25\,[0.5\,(XCA + XMAC) + XSD + XTP] \quad \ldots\ldots\ldots\ldots \quad (12)$$

As defined, the LEI is a simple number that ranges from 0–100 and is related primarily to clean water as affected by productivity problems, i.e., eutrophication.

Application to other problems would require modification or the development of other concepts, or both.

Case Examples

Shagawa Lake, Minnesota.—Shagawa Lake, in northeastern Minnesota, was the recipient of secondarily treated wastewater from the city of Ely (population 5,000) until early 1973, when a tertiary wastewater treatment plant (for phosphorus removal) began operation and reduced the wastewater phosphorus content from ~4.5 $mg \cdot l^{-1}$ to less than 0.05 $mg \cdot l^{-1}$. Prior to tertiary treatment, wastewater phosphorus accounted for ~80% of the external-phosphorus loading to the lake; after the tertiary treatment (early 1973 through 1975), wastewater accounted for ~6% of the post-treatment external-phosphorus loading. The lake is characterized by relatively rapid water flow through; the water retention time ranges from 0.4 yr–1.3 yr and the pretertiary treatment phosphorus retention time was about 0.5 yr, thus the lake would be expected to respond promptly to the 80% reduction in external P loading.

TABLE 6.—LEI Values for Target Variables, July–August, 1971–1976, Shagawa Lake, Minnesota

Year (1)	XSD (2)	XTP (3)	XTN (4)	XCA (5)	XDO (6)	XPMAC (7)	LEI (8)
1971	51.6	63.0	73.9	61.4	21.9	26.0	44.8
1972	55.4	60.6	81.1	64.4	28.8	26.0	47.0
1973	50.4	61.4	69.0	61.9	21.6	26.0	44.3
1974	45.7	57.0	64.2	57.6	21.8	29.5	42.3
1975	49.8	58.1	64.8	61.5	19.1	22.5	42.2
1976	51.7	58.1	68.1	65.0	23.2	26.0	44.8

Since four years of post-treatment data and two years of pretreatment data covering the selected LEI variables were available, the recovery of Shagawa Lake is used to illustrate the LEI (14). Table 6 presents the values for the LEI calculated from the equations described previously. Each target variable (except PMAC) is the average of nine weekly samplings during July and August each year. Macrophyte surveys were conducted during 1974 and 1975 (16). For illustrative purposes, the mean 1974–1975 PMAC score was used for 1971–1973 and 1976.

Individual target values suggest some improvement in the lake during post-treatment years, particularly in XSD (1974 and 1975) and XTP, although XCA and XDO remain relatively stable, with the exception of the high 1972 XDO value. The five variables (excluding XTN) combined according to Eq. 1 produce a relatively stable LEI which implies that during the July–August periods, Shagawa Lake has not responded markedly to wastewater P reduction. An indication of lower values is seen during 1974 and 1975 when compared with the values for 1971–1973, but LEI for 1976 is similar to the 1971–1973 values. The lack of major response of the lake during the July–August period is attributed to a significant release of phosphorus from sediments during these months which

stimulated algal growth and produced pretreatment Secchi transparency levels (14). The XDO might not be expected to respond rapidly to nutrient curtailment because high sediment oxygen demand would not be expected to diminish rapidly. This example implies that although movement is noted in some of the variables, the overall quality of the lake during summer as expressed by the LEI has not changed markedly during this period. Although the spring chlorophyll and phosphorus concentrations have declined markedly in post-treatment years, the summer concentrations have not improved sufficiently to change the LEI (14).

Medical Lake, Washington.—Medical Lake, located about 24 km southwest of Spokane, Washington, exhibited high concentrations of phosphorus, algal blooms and mats, and bottom waters depleted of oxygen. These conditions were attributed to phosphorus supplied by algal decomposition from previous blooms and from the lake sediments (8). The lake has exhibited these conditions for many years, and even though the community around the lake was sewered in 1964 in order to transport wastewater away from the lake, no substantial change in quality had been observed (1).

In late summer, 1977, Medical Lake was treated with alum, an effective phosphorus inactivant. Data obtained biweekly during July and August after

TABLE 7.—LEI Values for Target Variables July–August, 1977–1978, Medical Lake, Washington

Year (1)	XSD (2)	XTP (3)	XTN (4)	XCA (5)	XDO (6)	XPMAC (7)	LEI (8)
1977	43.9	76.5	91.0	50.8	67.2	20.0	55.8
1978	39.9	58.3	80.0	41.9	44.7	14.0	42.7

treatment were available for total phosphorus, Secchi depth, temperature, dissolved oxygen, chlorophyll-a, and total nitrogen, according to a personal communication from Gasperino and Soltero. Gasperino reports that macrophytes are essentially nonexistent in Medical Lake; they did not obtain estimates of macrophyte distribution and abundance. McConnell et al. (19) reports that 5% of the surface area of Medical Lake was covered with emersed plants and <1% of the lake bottom was covered with submersed plants in summer, 1973. These latter values were used to calculate PMAC from the surface area corresponding to a depth contour equal to twice the July–August Secchi depth. Values for XTP, XCA,and XTN were calculated for the upper 6 m of the lake.

Table 7 summarizes individual transformed values for each of the variables and the calculated LEI from Eq. 12. Significant decreases in each are seen. The decrease in PMAC occurs because increased Secchi depths imply a greater area which could be occupied by macrophytes. It is probable that if macrophyte areal coverage had been measured each year, PMAC would have been somewhat different, but because its magnitude is not large, the effect of year-to-year differences on the LEI value is probably not great. The decrease in the LEI (Table 7) displays the overall improvement in Medical Lake associated with treatment.

Summary and Conclusions

A lake evaluation index (LEI) was developed to evaluate restoration manipulation(s) applied to a specific lake and to evaluate specific restoration techniques by studying a set of lakes. Although to a certain extent the nutrient-mass balance approach appears reasonable for phosphorus and has been accepted for managing lakes, a review of the literature reveals that little consensus exists on the development of broader indices for evaluating lake quality.

The LEI proposed here has a conceptual basis and includes the most commonly used target variables for limnological analysis of lakes, i.e., Secchi depth (SD), total phosphorus (TP), total nitrogen (TN), chlorophyll-a (CA), net dissolved oxygen (net DO), and percent macrophytes (PMAC). Some of the target variables and associated data will be used in a quality assurance program to insure that comparable data from many lakes are obtained.

The LEI was not formulated as a trophic state index per se but rather to assess changes in a lake following restoration. It has a number of advantages. Transformation of data for each variable into scalar values tends to normalize the variables so that lakes of diverse morphometry or subject to different restoration techniques, or both, might be compared. Also, the scales of the variables are absolute rather than relative, which means the index is not limited to the set of lakes from which the developmental data were extracted. Use of the LEI by lake managers will permit them to assess water quality changes by monitoring shifts in the index numbers of individual variables or to combine the individual indices to produce a single number assessment of water quality. Application of the LEI to two lakes that have been restored indicated that the LEI is responsive to lake restoration efforts that actually produce changes in lake quality. The effects of some restoration techniques are not seen immediately and the LEI reflected this time lag in response.

Appendix I.—References

1. Bauman, L. R., and Soltero, R. A., "Limnological Investigation of Eutrophic Medical Lake, Washington," *Northwest Science*, Vol. 52, 1978, pp. 127–136.
2. Carlson, R. E., "A Trophic State Index for Lakes," *Limnological Oceanography*, Vol. 22, 1977, pp. 361–369.
3. Chapra, S. C., and Tarapchak, S. J., "A Chlorophyll-a Model and its Relationship to Phosphorus Loading Plots for Lakes," *Water Resources Research*, Vol. 12, 1976, pp. 1260–1264.
4. Dillon, P. J., and Rigler, F. H., "A Test of a Simple Nutrient Budget Model Predicting the Phosphorus Concentration in Lake Waters," *Journal of the Fisheries Research Board of Canada*, Vol. 31, 1974, pp. 1771–1778.
5. Dobson, H. R. H., Gilbertson, M., and Sly, P. G., "A Summary and Comparison of Nutrients and Related Water Quality in Lakes Erie, Ontario, Huron and Superior," *Journal of the Fisheries Research Board of Canada*, Vol. 31, 1974, pp. 731–738.
6. Edmondson, W. T., "Nutrients and Phytoplankton in Lake Washington," *Nutrients and Eutrophication*, G. E. Likens, ed., *Limnological Oceanographical Special Symposium*, No. 1, 1972, pp. 172–196.
7. Fee, E. J., "The Vertical and Seasonal Distribution of Chlorophyll in Lakes of the Experimental Lakes Area, Northwestern Ontario: Implications for Primary Production Estimates," *Limnological Oceanographical Special Symposium*, Vol. 21, 1976, pp. 767–783.
8. Gasperino, A. F., Soltero, R. A., Keizur, G. R., Nichols, D. G., and Kannberg, L. D., "Restoration of Eutrophic Medical Lake, Washington, by Treatment with

Aluminum Sulfate: Preliminary Findings," *Report to Town of Medical Lake*, Battelle Pacific Northwest Laboratories, 1978.
9. Goldman, C. R., "Eutrophication of Lake Tahoe Emphasizing Water Quality," *EPA-660/3-74-034*, Corvallis, Oreg., 1974, p. 408.
10. Holm-Hansen, O., Goldman, C. R., Richards, R., and Williams, P. M., "Chemical and Biological Characteristics of a Water Column in Lake Tahoe," *Limnological Oceanography*, Vol. 21, 1976, pp. 548–562.
11. Hutchinson, G. E., *A Treatise on Limnology—Volume I: Geography, Physics and Chemistry*, John Wiley and Sons, Inc., New York, N.Y., 1957, p. 1015.
12. Jones, J. R., and Bachmann, R. W., "Prediction of Phosphorus and Chlorophyll Levels in Lakes," *Journal of the Water Pollution Control Federation*, Vol. 48, 1976, pp. 2176–2182.
13. Landner, L., "Eutrophication of Lakes," World Health Organization, Regional Office for Europe, Copenhagen, Denmark, 1976, p. 78.
14. Larsen, D. P., Van Sickle, J., Malueg, K. W., and Smith, P. D., "The Effect of Wastewater Phosphorus Removal on Shagawa Lake, Minnesota: Phosphorus Supplies, Lake Phosphorus and Chlorophyll-a," *Water Research*, Vol. 13, 1979, pp. 1259–1272.
15. Lasenby, D. C., "Development of Oxygen Deficits in 14 Southern Ontario Lakes," *Limnological Oceanography*, Vol. 20, 1975, pp. 993–999.
16. Lie, G. B., "Phosphorus Cycling by Freshwater Macrophytes—The Case of Shagawa Lake," thesis presented to the University of Minnesota, at Minneapolis, Minn., in 1978, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
17. Lueschow, L. A., Helm, J. M., Winter, D. R., and Karl, G. W., "Trophic Nature of Selected Wisconsin Lakes," *Transactions of the Wisconsin Academy of Sciences, Arts and Letters*, Vol. 58, 1970, pp. 237–264.
18. Malueg, K. W., Tilstra, J. R., Schults, D. W., and Powers, C. F., "Limnological Observations on an Ultra-Oligotrophic Lake in Oregon, USA," *Verh. Int. Ver. Limnol.*, Vol. 18, 1972, pp. 292–302.
19. McConnell, J. B., Bortleson, G. C., and Innes, J. K., "Data on Selected Lakes in Washington, Part 4," *Water Supply Bulletin 42*, Part 4, Washington State Department of Ecology, 1976, p. 141.
20. Miller, W. E., Maloney, T. E., and Greene, J. C., "Algal Productivity in 49 Lake Waters as Determined by Algal Assays," *Water Resources Research*, Vol. 8, 1974, pp. 667–679.
21. Mortimer, J., "The Exchange of Dissolved Substances Between Mud and Water in Lakes," *Journal of Ecology*, Vol. 29, 1941, pp. 280–329.
22. "Water Quality Criteria 1972," *EPA-R3-73-033*, National Academy of Sciences-National Academy of Engineers, Superintendent of Documents, 1973, p. 594.
23. Porcella, D. B., and Peterson, S. A., "Evaluation of Lake Restoration Methods: Project Selection," *CERL-034*, United States Environmental Protection Agency, Corvallis, Oreg., 1977, p. 34.
24. Porcella, D. B., Peterson, S. A., and Larsen, D. P., "Proposed Method for Evaluating the Effects of Restoring Lakes," *Limnological and Socio-Economic Evaluation of Lake Restoration Projects—Approaches and Preliminary Results, EPA-600/3-79-005*, United States Environmental Protection Agency, Corvallis, Oreg., 1979, pp. 265–310.
25. Rodhe, W., "Crystallization of Eutrophication Concepts in Northern Europe," *Eutrophication: Causes, Consequences, Correctives*, National Academy of Sciences, 1969, pp. 50–64.
26. Sakamoto, M., "Primary Production by Phytoplankton Community in Some Japanese Lakes and its Dependence on Lake Depth," *Archives of Hydrobiology*, Vol. 62, 1966, pp. 1–28.
27. Sawyer, C. N., "Fertilization of Lakes by Agricultural and Urban Drainage," *Journal of the New England Water Works Association*, Vol. 61, 1947, pp. 101–127.
28. Shannon, E. E., and Brezonik, P. L., "Eutrophication Analysis: A Multivariate Approach," *Journal of the Sanitation Engineering Division*, ASCE, Vol. 98, No. 1, Proc. Paper 8735, Feb., 1972, pp. 37–57.
29. "An Approach to a Relative Trophic Index System for Classifying Lakes and Reservoirs," *Working Paper No. 24*, United States Environmental Protection Agency, Corvallis, Oreg., 1974, p. 35.
30. "A Compendium of Lake and Reservoir Data Collected by the National Eutrophication

Survey in the Northeast and North-Central United States," *Working Paper No. 474*, United States Environmental Protection Agency, Corvallis, Oreg., 1975, p. 210.
31. Vollenweider, R. A., "Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication," *Organization for Economic Cooperation and Development Technical Report, DAS/CSI/68.27*, Organization for Economic Cooperation and Development, 1968, p. 182.
32. Vollenweider, R. A., "Advances in Defining Critical Loading Levels for Phosphorus in Lake Eutrophication," *Mem. Ist. Ital. Idrobiol.*, Vol. 33, 1976, pp. 53–83.
33. Winner, T. W., "An Evaluation of Certain Indices of Eutrophy and Maturity in Lakes," *Hydrobiologia*, Vol. 40, 1972, pp. 223–245.

Appendix II.—Notation

The following symbols are used in this paper:

CA = chlorophyll-a;
CDO = instantaneous measured total lake DO;
DO = dissolved oxygen;
EDO = instantaneous equilibrium DO;
I = light intensity;
Io = surface light intensity;
LEI = lake evaluation index;
n = vertical light attenuation coefficient;
PMAC = percent macrophyte coverage;
SD = Secchi depth;
TN = total nitrogen;
TP = total phosphorus;
TSI = trophic state index;
V = lake volume;
Vi = lake volume for depth increment *i*;
XCA = transformed chlorophyll-a;
XDO = transformed DO;
XMAC = transformed percent macrophyte coverage;
XSD = transformed Secchi depth;
XTN = transformed total nitrogen;
XTP = transformed total phosphorus;
Z = water depth; and
ZMAX = maximum lake depth.